PHYSICS OF FAILURE

A Science-Based Approach to Ultra-High Reliability

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In this time of decreasing budgets, great emphasis is placed on doing more for less. System reliability is an area where great savings can be accomplished by utilizing design and assessment methodologies which address the root causes of failure (i.e., a physics-of-failure (POF) approach). Using such science-based reliability techniques early in the design process can yield great cost savings in manufacturing, testing, fielding and sustainment of a new system. Additionally, a POF approach is needed to assess the reliability cost impacts of utilizing commercial and new technologies in system design.

Modern military systems rely heavily on large quantities of electronics. System readiness depends to a great extent upon the reliability of the electronics. Each electronic subsystem with its associated circuit card assemblies (CCAs) and individual components must be reliable, without unexpected failure during the service life of the system. Selection of a reliability assessment approach is a fundamental choice made by those concerned with the cost-effective design of reliable electronic hardware.

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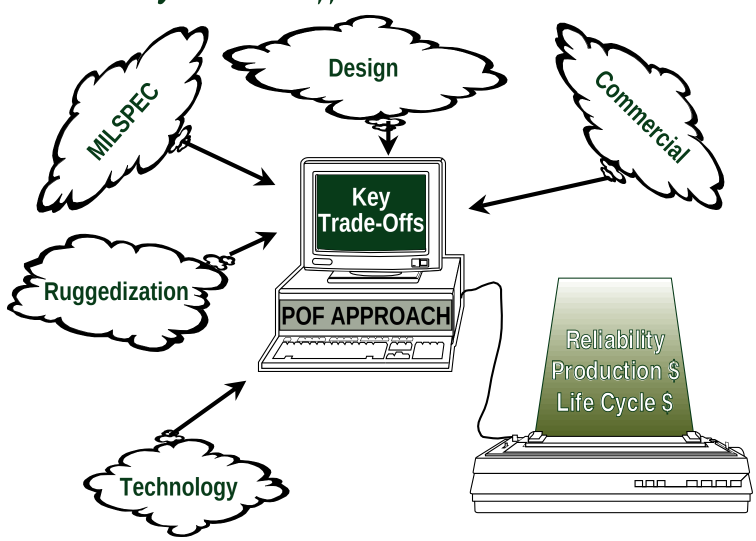
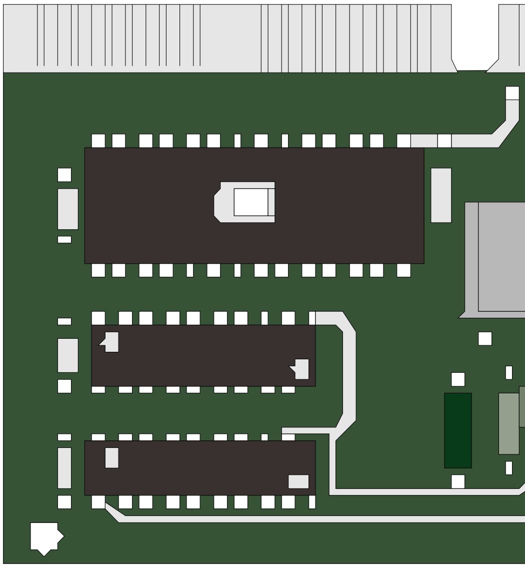
FIGURE 1. Key Trade-offs



Key trade-offs between commercial vs. military specification components, ruggedized vs. nonruggedized boards, emerging vs. traditional technology, and design layout (Figure 1) occur early in a program and can significantly impact the reliability and life-cycle costs of a system. The POF modeling and simulation tools provide program managers (PMs) and system designers with a science and engineering based approach for evaluating these types of trade-offs that can profoundly impact a program.

Concept

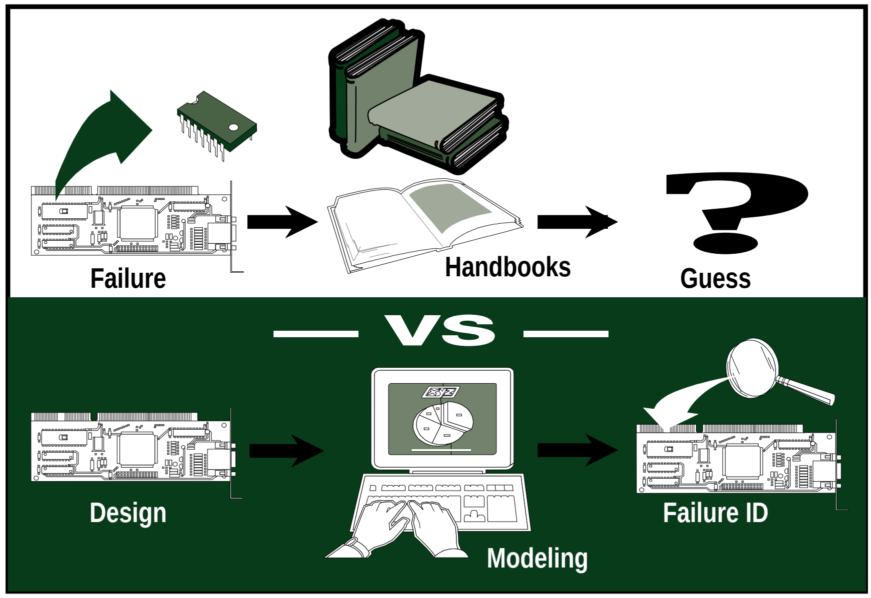
Traditional reliability assessment techniques for microelectronics are based on empirical models fitted to field data and are available in several handbooks. These techniques have long been criticized for their shortcomings. This concept of reliability, normally quantified by assessing the mean time between failures, implies that field failure is inevitable. The



empirical failure models used by these handbooks are typically not derived from, or based on, any physics or mechanics of failure, and as such, they do not give the designer insight into, or control over, the actual failure mechanisms. Thus when designing, screening and testing a new product or a product with new technologies, these models may be inappropriate and misleading.

Until recently, these techniques have continued to survive since there has been no viable alternative. Now the POF approach exists — a practical, science-based alternative. In contrast to the "traditional" approach, the POF approach uses modeling and simulation techniques to identify first-order failure mechanisms prior to physical testing (Figure 2). The POF technology and computer tools have been developed by the Computer-Aided Life-Cycle Engineering (CALCE) Electronic Packaging Research Center (EPRC) at the University of Maryland with the support of industry, government and other universities. The U.S. Army Materiel Command (AMC), with the U.S Army Materiel Systems Analysis Activity (AMSAA) as the Army lead activity, has supported the POF technology development efforts which have produced microelectronic device design tools that eliminate sources of failure early in the design process, thereby reducing required testing, shortening the development cycle, and increasing weapon system reliability.

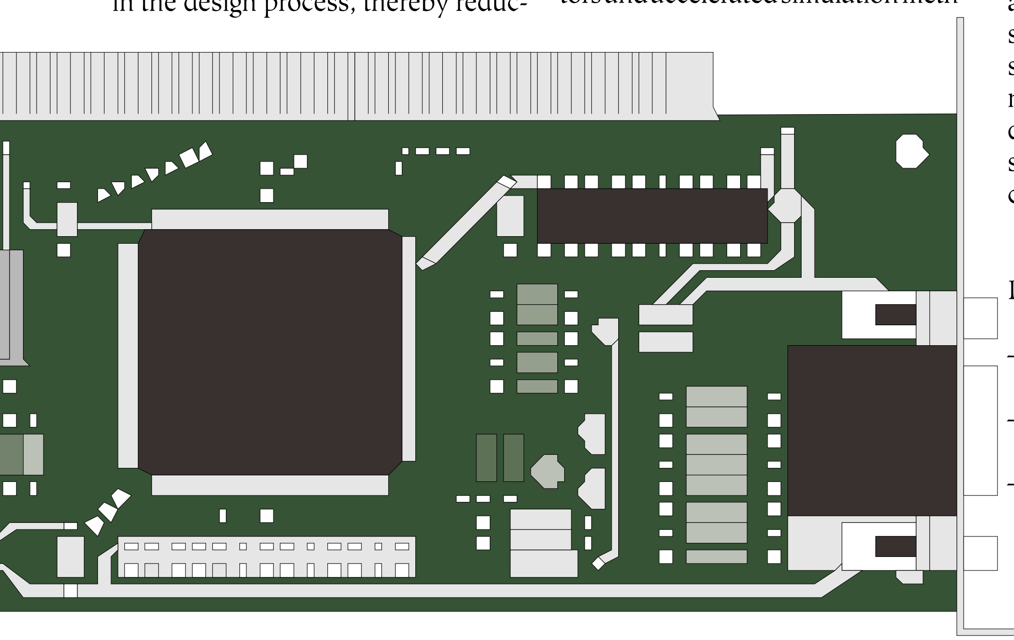
FIGURE 2. Traditional vs. POF Techniques



The POF is an up-front approach to reliability that focuses on preventing failures through robust design and manufacturing practices based on: life-cycle loads and stresses, product architecture, and potential defects and failure mechanisms. The approach incorporates reliability in the design process by establishing a scientific basis for the evaluation of new materials, structures and technologies, and by designing tests, screens, safety factors and accelerated simulation methods. The approach incorporates reliability in the manufacturing process through understanding how to best utilize and enhance manufacturing capabilities to promote high quality. The traditional reliability assessment techniques heavily penalize new materials, structures and technologies because of the lack of sufficient failure data. This approach, based on the "fear of the unknown" rather than any science-based analysis, discourages change, hindering the process of reliability enhancement. The POF approach, on the other hand, is based on physical failure models which are as effective for new materials and structures as they are for existing designs. The new approach is a dual-use method which encourages innovative designs by a realistic reliability assessment whether the application is commercial or military.

The basic steps to implement the POF approach are the following:

— Define realistic product requirements.
— Define the design usage environment.
— This usage profile defines the mechanical, thermal, electrical and chemical loads that are experienced over time. These loads may



be associated with manufacturing, testing, storage, repair, handling and operating conditions.

— Identify potential failure sites and failure mechanisms. Critical parts and their interconnections, and potential failure mechanisms and modes must be identified early in the design. Potential architectural and stress interactions also must be defined.

— Characterize the materials and the manufacturing and assembly processes. To assume structures are free of defects is unrealistic and potentially dangerous. Materials often have naturally occurring defects, and manufacturing processes can induce additional defects.

— Design to the usage and process capability. The design stress spectra, the part test spectra, and the full-scale test spectra must be based on the anticipated life-cycle usage conditions. These steps become an iterative process of system design, design analysis and system redesign (Figure 3) to develop a reliable cost-effective product that meets some set of realistic requirements.

Tools

The POF modeling and simulation tools (Figure 4) are key elements in the overall POF approach of determining the robustness of the system design and manufacturing practices with respect to reliability. Two such computer-based modeling and simulation tools are called Computer-Aided Design of Microelectronic Packages (CADMP-2) and Computer-Aided Life-Cycle Engineering (CALCE). The CADMP-2 assesses the reliability of electronics at the package level while CALCE assesses the reliability of electronics at the printed wiring board level. Together, these two models provide a framework to support a POF approach to reliability in electronic systems design.

FIGURE 3. POF Design Process

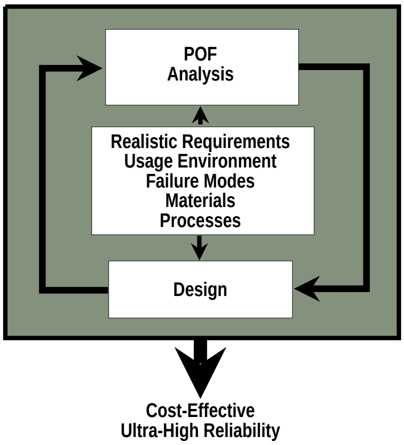
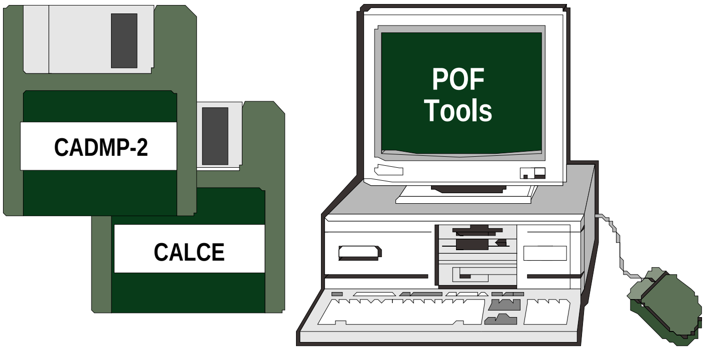


FIGURE 4. Tools to Support an Overall POF Approach



CADMP-2

The CADMP-2 is a set of integrated software programs that can be used to design and assess the reliability of integrated circuit, hybrid and multichip module packages. The CADMP-2 was developed by the CALCE EPRC of the University of Maryland, and is based on the POF approach to electronic package design. The CADMP-2 aids in assessing component reliability during the design phase; evaluating new materials, structures and technologies; assessing packages designed by other software programs or manufacturers; and developing cost-effective products.

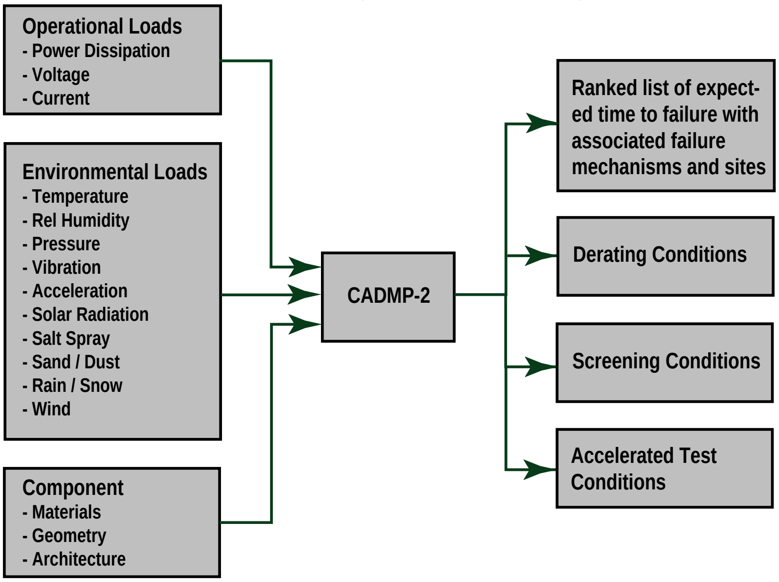
The CADMP-2 software tools are used to assess the reliability of packages subjected to different environments and design constraints. An overview of the CADMP-2 inputs and outputs is shown in Figure 5. The CADMP-2 also aids in the selection of package type, package-to-board mounting technology, interconnections and substrates. During the CADMP-2 assessment process, an average time to failure is determined for each potential failure mechanism using models based on package geometric and material parameters, as well as the environment in which the package will function. Potential failure mechanisms at the potential failure sites can be ranked to identify weak links in the package. The CADMP-2 performs thermal stress analysis including conductive and convective analysis. Calculations are based on data stored in material, environment, failure mechanism and parts libraries.

CALCE

The CALCE software provides an integrated design environment used to incorporate various tools associated with reliability, supportability, producibility and costing tasks into the design of electronic systems in the earliest stages of the design process. The CALCE software was developed by the University of Maryland CALCE center and is based on a POF approach to printed wiring board design.

The CALCE software is a set of integrated tools for the design and analysis of electronic assemblies. Figure 6 provides an overview of the CALCE input and outputs. The software can be used for the design of complex multilayer printed wiring boards, including the selection and placement of components. The CALCE software can determine the component junction, case and sub-

FIGURE 5. CADMP-2 Inputs and Outputs



strate temperatures. The software calculates component and system failure rates, vibrational effects on component leads, and thermal and mechanical solder joint fatigue for surface mount devices.

Applications

Generally, the work performed early in the development of a new or modified system focuses on performance, and does not take into account adequately the impact of other areas such as reliability. During this early period, pre-Milestone 0 to Milestone II, Integrated Product and Process Development can have its greatest impact. Traditionally, reliability has been sought through a Reliability Growth Test (RGT) program, which can be very expensive.

The POF methodology and computer tools can reduce the number of time-consuming and expensive hardware test iterations. In fact, it is becoming feasible to improve reliability in the conceptual design stage by connecting the contractor and the military reliability team members before expensive manufacturing commitments are made. Physics-of-failure methodology and design tools allow reliability engineering to become "proactive" rather than "reactive," and has numerous applications throughout the materiel acquisition cycle (Figure 7).

Accelerated Testing

Test time and money can be reduced significantly by using accelerated testing. However, a way must exist to evaluate equipment reliability based on accelerated test results. Since different failure mechanisms follow different life distributions, they also may have different acceleration models. To properly develop an accelerated test methodology to reduce testing, a POF approach is required. The POF methodology can be used to design specific accelerated tests as well as general testing guidelines to ensure the testing can be correlated correctly with equipment reliability. An accelerated life test on the main processor CCA for the U.S. Army Joint STARS program will be conducted using the CALCE and CADMP-2 POF tools to determine failure mechanisms and assist in the accelerated test design. The accelerated test will be used to determine if a commercial CCA is as reliable as a ruggedized CCA to be used in the light ground station module. Cost savings for the commercial ($6,000) vs. the ruggedized ($19,000) CCA is substantial.

Logistics

The POF concepts can improve depot maintenance of electronic equipment in three areas: failure verification and isolation, improved reliability after repair, and improved repair verification. When an electronic item comes into the depot for corrective maintenance, depot maintainers frequently are unable to detect failure resulting in no evidence of failure (NEOF). Many of these NEOFs are due to failure modes which are intermittent or marginal, and multiple field failures can result from one intermittent or marginal failure. For example, a solder connection on a CCA is expected to fail due to fatigue resulting in an intermittent electrical connection that is only detectable at a particular vibration profile. At present, depot maintainers run diagnostics at

FIGURE 6. CALCE Inputs and Outputs

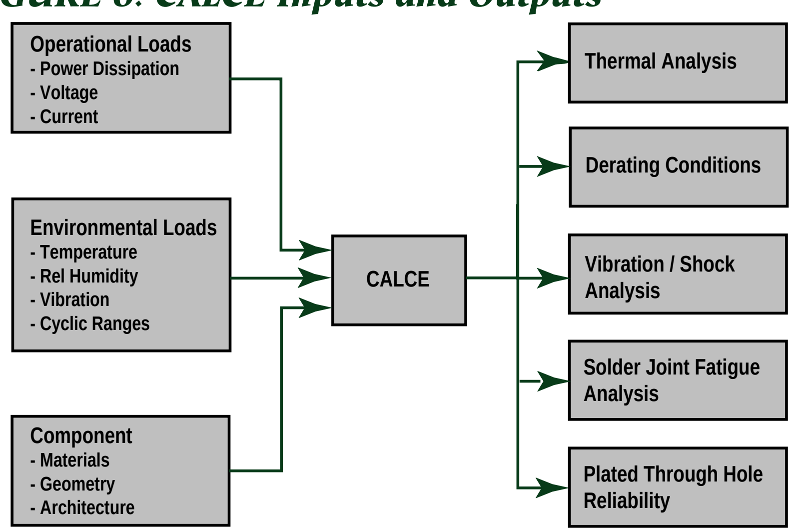
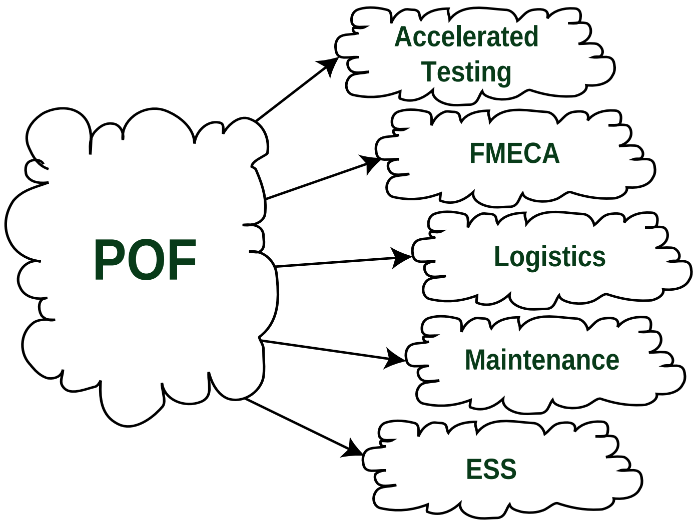


FIGURE 7. POF Applications



benchtop conditions and would categorize the CCA as NEOF. With the POF approach, operational and environmental loading profiles for failures most likely to occur would be used for failure verification.

Maintenance

Currently, unfailed electronic items are erroneously assumed to be as "good-as-new" items. However, many failures in electronics are due to wearout. With the POF approach, the good-as-new assumption would not be used during development of repair procedures. For example, if a CCA has wearout failures of two integrated circuits which are expected to occur at similar amounts of usage, the current approach is to replace only the first integrated circuit that failed. The CCA is then assumed, incorrectly, to be as good as a new CCA. Utilizing the POF approach, both integrated circuits would be replaced when one failed.

Environmental Stress Screening

Repair of an item can introduce defects just as much or more than original manufacturing. Currently, the depots are instituting environmental stress screening (ESS), usually relying on temperature cycling and vibration, to precipitate defects introduced during repair. A POF approach can help eliminate much of the guesswork required for the development of ESS procedures. The ESS procedures are supposed to be designed to use up, at most, 10 percent of the useful life of the item. This is especially important for the used items that depots repair. A POF analysis is the only way to determine how much useful life remains.

FMECA

Currently, the failure modes and effects criticality analysis (FMECA) on electronics components are based on a functional approach that does not account for many of the actual failures in the field. The potential of hardware approach FMECA has not been able to be exploited since the reliability technology required to accurately determine the key hardware failure modes, the stress conditions required for their detection, and their likely order of occurrence has not been available for modern electronic CCAs and for the microelectronic devices that populate these assemblies. For example, the FMECA assumes the integrated circuits either failed open or failed short. This is not necessarily representative of how cards and devices will actually fail, and does not account for the subtle intermittent or marginal failure modes. Using POF automated reliability assessment tools can provide expected failure times, sites and stress drivers for the key failure mechanisms associated with an electronic CCA.

Summary

The implementation of the POF methodology into the materiel acquisition process can yield significant cost savings (Figure 8). The earlier POF methodology is applied to the process, the greater the potential cost savings. Physics-of-failure modeling and simulation tools provide PMs and system designers with the only science and engineering based approach for evaluating key design specification and technology trade-offs that can have a profound impact on a program. The advantages of applying the POF reliability assessment techniques to the materiel acquisition process surpasses those afforded by traditional reliability assessment techniques.

The Army has started POF research in the areas of mechanical systems, electro-optics, and box level electronics. Automated modeling and simulation tools that assist in the application of an overall POF approach will be developed for each of these research areas. The electronic component and circuit card level tools (CADMP-2, CALCE) have been completed, and are available for designers to use as tools to support an overall POF approach, prior to the completion of a comprehensive electronic tool set.

FIGURE 8. POF Applied to Material Acquisition Process